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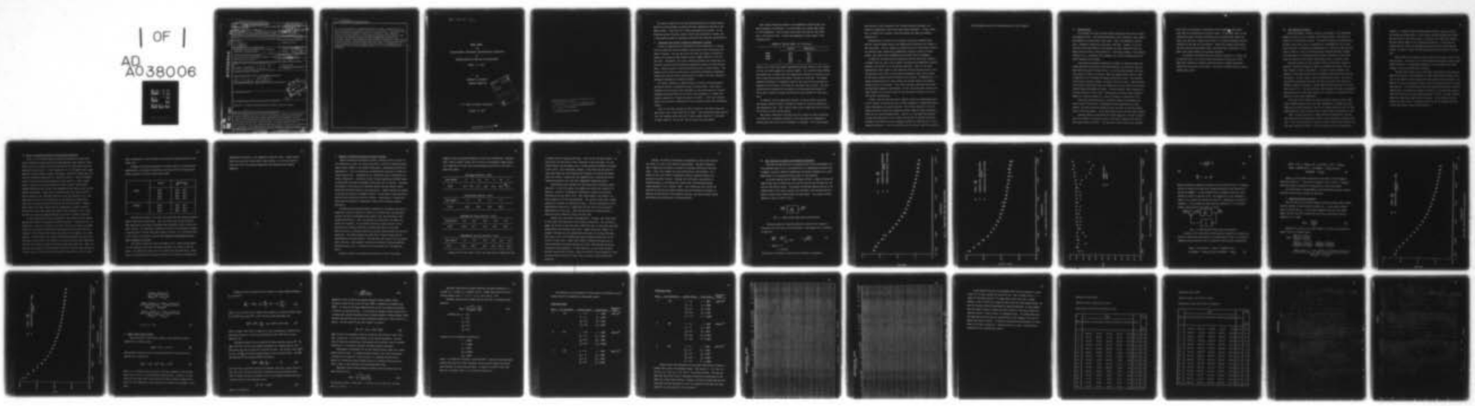

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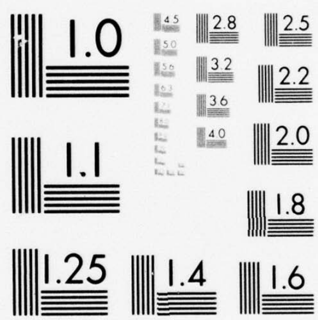
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Various approaches were used.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The overall objective of this research effort was to explore several possible training methods to produce efficient compensatory tracking in the Rhesus monkey. Toward this end, various approaches were utilized. Several animals were successfully trained and a five-parameter model was developed to describe this behavior mathematically. A major finding was that no detrimental effects were evidenced following a shift from pursuit to compensatory tracking. This finding agrees with the findings of others in human

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20. tracking situations and ~~thereby~~ illustrates another similarity between human and subhuman response to discrete tracking tasks. The study showed that no special retraining procedures are required to train subhuman primates on either pursuit or compensatory tracking and this feature, that of a universial training method, was ~~one of the~~ a primary goal~~s~~ of this research. Another major finding ~~of this effort~~ was that, based on the assumption that low doses of tranquilizing drugs may improve tracking efficiency of shock conditioned animals, it appears that the effect of tranquilizers was dependent as much on the individual animal as it was on ~~the level of~~ dose level. employed.

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AFOSR - TR - 77 - 0377

ANNUAL REPORT

for

THE DEVELOPMENT, MAINTENANCE, AND MATHEMATICAL DESCRIPTION

of

TRACKING BEHAVIOR IN MAN AND THE RHESUS MONKEY

AFOSR - 75 - 2751

by

UNIVERSITY OF KENTUCKY

RESEARCH FOUNDATION

D. F. McCoy, Principal Investigator

November 19, 1976

The overall objective of the work described below was to explore several possible training methods to produce efficient compensatory tracking in the Rhesus monkey. Toward this end, various approaches were utilized. As the following sections indicate, several animals were successfully trained, and a five-parameter model was developed to describe this behaviour mathematically.

I. Transition from Pursuit Tracking to Compensatory Tracking

In order to appreciate the significance of this manipulation, it should first be noted that the early phases of this project dealt exclusively with pursuit tracking. This was due to the fact that the original training procedures were developed under another contract (AFOSR F33615-72-C-1112) for this task. Furthermore, the pursuit tracking equipment had already been constructed, and while the more preferred compensatory system was under development, a series of pursuit tracking sessions was given to three animals. The purpose of this initial session was to re-establish asympototic performance levels which could be used as baseline data to compare with those obtained in subsequent compensatory tracking situations.

All animals received our standard series of pursuit tracking exposures. Each daily session is comprised of three 15-minute blocks. Each block is sectioned into 30 second trials separated by a 30 second intertrial interval. Although the precise effect of this set of time parameters is unknown (see proposed research for a factorial study of "on time" -- "off time" relationships) this particular combination of time variables has met with considerable success.

Prior to the shift, percent of time on target for the pursuit task averaged 96.4%, with a range from 92.6% to 99.8%. These values were based upon the last five sessions before the shift in which target width was 1.0 inch with an input signal of .122 cps and .163 cps (sum of two sine waves).

Next, these animals were placed on the compensatory tracking task, the basic parameters of which were a 1.0 inch target and a random input signal of .05 Hz bandwidth. Time on target scores were collected for each animal over a five session block. Pursuit and compensatory scores appear in the following table.

PERCENT OF TIME ON TARGET, TOT (5 sessions)

		Pursuit		Compensatory
#065H		99.8		94.7
#065B		96.9		99.0
#476B		92.6		69.9
	$\overline{X}$	96.4	$\overline{X}$	87.5

Clearly, two of the three animals manifested negligible effects of the transfer. In fact, one animal appeared to improve slightly. For the third animal (#476B) the reduced time on target score for compensatory tracking is due solely to the first session during which this animal "tracked" at a mere 54%. This monkey improved considerably in subsequent sessions, and, when the first session was dropped from the analysis, TOT scores for the animal rose to 89.6%. With this corrected value inserted into the analysis, the group mean was elevated to 94.4%, which compares favorably with the 96.4% value obtained for the pursuit task.

In addition, and for comparative purposes, two naive animals were given the standard response shaping, followed by a block of five daily sessions on the compensatory task. Their time on target scores ranged from 76.4% to 83.0% ($\overline{X}$ of 78.2%) for the five-day period.

The overall conclusion to be drawn from this research is that no detrimental effects are in evidence following a shift from pursuit to compensatory tracking when the current set of parameters is employed. This finding agrees

with Poulton's (1974) conclusion that in human tracking situations, the pursuit-to-compensatory shift can be made without decrement. It does, therefore, illustrate still another similarity between the human and subhuman tracking task.

Unfortunately, the other half of Poulton's conclusion regarding asymmetrical transfer between pursuit and compensatory tracking was not tested in this experiment. That is, because the primary mission of the present research was directed toward establishing compensatory tracking in pursuit trained animals, the reverse shift (compensatory-to-pursuit) was not attempted.

In addition, and based upon the comparison with the two control subjects, it appears that not only is the transfer from pursuit-to-compensatory tracking possible, the transfer is in the positive direction: That is, the three experimental animals appear to have benefited from the previous pursuit tracking experience since their scores ranged considerably higher than did those of the control subjects which received no such training. Parenthetically, it should be mentioned that at this writing, the control animals are showing a steady increase in TOT scores. Thus, their previously mentioned scores were not based upon asymptotic performances. In fact, the acquisition functions for these subjects are similar to those of the experimental animals on the original pursuit tracking task.

Finally, the fact that the control subjects learned the compensatory task at all, attests to the fact that our training procedure is indeed applicable to either compensatory or pursuit tracking. The critical features of this procedure have been spelled out elsewhere (Lafferty, Edwards, McCoy, McCutcheon, 1973) and will not be belabored here. Suffice it to say that the procedure we have developed appears to fit either task and that no special retraining procedures are required to train subhuman primates on either pursuit- or compensatory tracking. It will be recalled that this feature, that of a universal

training method, was one of the primary goals of this research.

II. Titrated Shock

Our standard training procedure employs continuous high levels of shock at programmed rates. The presumed advantage of this technique is that immediate feedback is provided when errors occur. Also, the parameters involved (e.g., frequency, intensity) can be easily specified. However, it is also true that shock administered in this manner has other properties which probably adversely affect tracking behavior. One obvious example is the skeletal reactions (e.g., thrashing, stick slamming, etc.) which accompany shock and which interfere with tracking.

The titration procedure represents an attempt to remove the above mentioned emotional concomitants which shock produces, and yet retain shock as the controlling agent in these studies. For the present purposes, the titration concept is applied as follows: When the subject makes an error, shock is applied, but at a reduced (or perhaps nonaversive) level. The intensity of the shock increases, however, so long as the error exists. When the shock level becomes sufficiently high, the subject will correct the error by returning the controlled element to target. In this situation, shock intensity is a direct function of error time. In the present situation, shock intensity begins at 1 ma and increases at a rate of 1 ma/sec to a maximum of 5 ma.

During the reporting period, a titration shocker was purchased, and after several "false starts," programmed into the compensatory tracking system. One naive animal was shaped to hold, and later to move the control stick in the usual manner. It was then placed on the titration shock schedule.

Although premature conclusions are always dangerous, it does not appear that this subject is tracking as well as some other subjects which receive the standard-shock treatment. This particular animal seems to have learned

more slowly, and maintains a consistently lower asympototic performance level than the "conventionally trained" animals. On the other hand, we have learned that great individual differences exist between Rhesus monkey subjects, and, therefore, another naive animal is currently undergoing training according to the same set of parameters. Should this subject also manifest the same attenuated performance levels, then additional adjustments will be made in the shock schedule (see proposed research).

In principal, we believe that the titration technique is a viable one. At the same time, it is risky to draw conclusions at this point in time. Additional subjects are required along with certain schedule adjustments before firm conclusions can be drawn. This work is planned during the forthcoming grant period.

III. Food Maintained Tracking

Colony confinement, handling, chairing, confinement in the experiment chamber and shock are all stressful to the Rhesus monkey. This point was alluded to in the previous section. The overall effect of such factors may be that a high stress level is produced which interferes with, and in some cases prohibits, the learning and maintenance of a complex and delicate task such as tracking. While the above-described titration procedure attempts to retain shock as a reinforcing agent through a reduction in shock intensity, the present section focuses upon another source of control, food.

The basic features of this procedure involve training the subject to maintain a controlled element on target for progressively longer time periods in order to obtain food pellets. In order to avoid satiation, the subject is given food pellets only at programmed intervals during the tracking session. At other times, a tone is substituted for food. By virtue of its previous association with food, the tone has acquired the capacity to reinforce behavior secondarily. Actual tone-food pairings occur on a fixed ratio basis of 5:1. For each criterion time on target, the tone is presented. Food accompanies the tone (and maintains its strength as a conditioned reinforcer) on every fifth presentation.

The first animal studied was trained jointly on food and shock. When these reinforcing agents were later made independent, it became clear that shock was the overriding agent: That is, the subject would not work for food independently of shock, but would track to avoid shock independently of food.

Later in the grant period, a second animal was pretrained on the FR5 tone-food pairing and subsequently placed in the compensatory tracking situation. After a few sessions this animal's behavior became highly erratic, and TOT scores diminished rapidly. Mild food deprivation did not remendy the

situation. It appeared that the conditioned reinforcer (tone) was losing its reinforcing effectiveness. At this time, tracking sessions were halted and tone-food pairings were resumed. In spite of this additional training, the tone did not appear to be an effective reinforcer. It was also discovered that the animal was consuming progressively fewer sucrose pellets. Finally, it would no longer eat them when made freely available in the home cage.

Other animals have evidenced similar behaviors with other sorts of reinforcing agents. The decline in the reinforcing effectiveness of these conventional reinforcers is undoubtedly responsible for the highly erratic data yielded in the food-reinforcement situation.

The fact that we have not, at this point, established clearly that compensatory tracking can be maintained on a food reinforcement schedule, does not, in our opinion, vitiate against the basic premise of the procedure. Any behavior is only as strong and reliable as are the conditions used to support that behavior. If the reinforcers upon which the behavior depends lose their effectiveness, the behavioral output will diminish. This does not, however, reduce the utility of the food-tracking premise. Rather, it simply indicates that other reinforcing agents must be employed. We now believe that this problem has been solved. A complete description of the intended direction of this work appears under proposed research.

IV. Human vs. Subhuman Operators in Two Tracking Situations

As part of our ongoing program to study the comparative similarities and/or differences between human and monkey operators under identical situations, data were collected from these two species for both pursuit and compensatory tracking tasks. In this connection, it is of interest that a paper appeared recently (Bachman, Jaeger, and Newsom, 1976) which focused upon the issue of man-monkey comparisons in a tracking situation. Using an argument similar to that which we have employed for some time (i.e., that a monkey model is necessary for the application of stress to man), these authors argued convincingly that we must first demonstrate that these species do show similar performances. Based upon a primate-training task quite similar to that discovered in our laboratory some four years ago, Bachman, et al. produced results which do lend credibility to the monkey-man extrapolation since the two species did perform similarly on the task studies. However, their results were based solely upon the compensatory tracking situation. Our present results both support and extend those of Bachman, et al. since our data are based upon both compensatory and pursuit tracking situations.

In the initial phase of the investigation, four humans and three Rhesus monkeys were studied in the pursuit tracking situation. Target size was 1.0 inches and a sum of two sine waves (.122 and .163 cps) was used as the input. Trials were 30 seconds in duration and separated by a 30 second intertrial interval. Three fifteen-trial blocks were given to each subject in a single session. For the monkeys "off target" performances punished with shock. For the humans, these errors were punished on a error-cost basis which subtracted from the total amount of money ($3 maximum) which they could earn. Next, all subjects were studied in the compensatory tracking situation, characterized by a target size of 1.0 inches and input bandwidth varying from .05 to .15 cps.

Error contingencies, trial durations and intertrial intervals were as in the former task.

Although the fine-grained behavioral outputs remain to be analyzed and mathematized, a preliminary evaluation can be made from the following table based on percent of time-on-target scores (TOT).

	Pursuit	Compensatory .05	Compensatory .15
Humans	99.8	99.9	99.3
	99.6	99.5	99.3
	98.5	98.9	98.5
	96.7	97.6	97.4
Monkeys	99.8	94.7	94.2
	96.9	99.0	98.4
	92.6	89.6	90.8

From the above table, it is clear that both human and subhuman operators perform quite well on both tasks. Very few errors occur in any situation. More importantly, both human and monkeys show negligible effects of the parameter changes. The functional relationship between TOT and parameter changes is quite similar for each individual organism studied. It is the point which is of critical significance; viz that the functional relationships are the same, regardless of species.

The results, along with those of Bachman, et al., offer strong support for the contention that human and monkey operators are similar on the two tasks. Any differences which exist are quantitative not qualitative. Therefore, the emotionally-based argument offered by some that man and monkey are

fundamentally different is not supported by empirical fact. Further evaluation of this empirical issue awaits study, however, it is to this specific issue that two of the proposed experiments are addressed (See proposed research).

V. Effects of Tranquilizing Drugs on Pursuit Tracking

Before discarding the mechanical pursuit tracking facility in favor of the compensatory system, two animals were given a series of tracking sessions under various dosages of two tranquilizing agents, chlorpromazene (CPZ) and pentobarbital. CPZ is classified as an antipsychotic drug and is viewed as a "major tranqualizer." Pentobarbital is a barbituate, and is classified as a "minor tranqualizer." Relatively little is known regarding the effectiveness of these drugs on complex psychomotor activities such as tracking. Therefore, one purpose of the study was to determine whether the two chemical agents would have different effects on tracking ability. Another purpose was related to the earlier-mentioned "emotional effects" of high stress levels associated with the shock-maintained tracking situation. Specifically, it seemed possible that low dosages of tranquilizers could actually improve tracking efficiency.

As with many psychopharmacological experiments, the general plan was to establish a baseline, administer a drug at a low dose level, and gradually increase the dose on subsequent drug sessions until the performance level changed significantly. Next, for purposes of replication, the lower case levels were repeated. In the present situation, drugs were given intramuscularly at irregular intervals, but never more than one each week. Several non-drug, or placebo sessions were always spaced between any two drug conditions. One animal (Hoppy) was given CPZ at several dosages and the pentobarbital at several dosages. The drug order was reversed for the second animal, Big Boy. Both subjects received the "standard" tracking conditions described earlier (i.e., 30 second trials, 30 second ITI, full-intensity shock).

Computer analysis and mathematical description of the "fine grain"

aspects of the drug-produced behaviors is yet to be accomplished. Nevertheless, "time on target" scores, TOT (in terms of percentages), appear below. It is important to realize that the drug dosages were given in the order in which they appear.

CPZ (Hoppy) BASELINE = 99.8%

Dose (Mg/Kg)	.2	.5	1.0	.75	.5	.35	.2
% TOT	97.1	97.7	41.2	32.8	41.0	54.9	51.8

CPZ (Big Boy) BASELINE = 96.3%

Dose (Mg/Kg)	.2	.35	.2	.15
% TOT	92.2	40.0	76.2	95.2

PENTOBARBITAL (Hoppy) BASELINE = 99.8%

Dose (Mg/Kg)	5.0	8.0	12.0	3.5	5.0
% TOT	94.0	74.7	71.4	58.1	59.3

PENTOBARBITAL (Big Boy) BASELINE = 96.3%

Dose (Mg/Kg)	5.0	8.0	12.0	15.0	8.0	5.0
% TOT	90.5	88.0	90.1	41.0	86.3	89.1

Looking first at the effect of CPZ, the lowest dose (.2 Mg/Kg) had only

a slight effect on tracking efficiency. This was true for both animals. At this point, the similarity of their reactions to the drug ended. For one animal (Hoppy) increased doses up to 1.0 Mg/Kg produced systematic decreases in TOT scores. More interesting, however, is the fact that the return to lower dose levels was not accompanied by increases in tracking efficiency. Thus, this animal's response was dose dependent until tracking had become severely attenuated, but it was dose independent beyond that point.

A different picture emerged with the second animal (Big Boy) studied under CPZ. In the first place, this monkey was clearly more sensitive to the drug. A dose of .35 Mg/Kg was sufficient to surpress his tracking efficiency below the chance level. More interestingly, this animal's behavior appears to be more dose-dependent. The return to lower doses yielded progressive increases in tracking efficiency. The only discrepency in this generalization occurred at .2 Mg/Kg were TOT was 16% less on the second administration of this dose. This was due mainly to a single episode in which the animal removed his hands from the stick.

Consider now, the effect of pentobarbital. Clearly, much larger doses of this agent were required to affect behavior measurably. For one animal, Hoppy, the effect was much the same as with CPZ; that is, TOT scores decreased progressively with increases dose level. Beyond this point, however, decreases in dosage were not accompanied by increases in tracking efficiency. TOT scores at 3.5- and 5.0 Mg/Kg were both considerably below that at the initial 5.0 dose level. Again, this animal's tracking efficiency was at first decreased by increasing dosages, but later, TOT remained low and was unrelated to dose magnitude. In sharp contrast, was the effect of pentobarbital second animal, Big Boy. Again, the effect of dose strength or tracking efficiency was inverse; as dose level increased, tracking efficiency decreased.

Clearly, the effect of both drugs was dependent as much on the individual animal as it was on the specific dose employed. The most interesting case is Hoppy who was unable to recover his tracking efficiency at any dose level. Still, this subject did track effectively on non-drug days. As a matter of fact, this animal's performance actually improved slightly over successive baseline sessions. Perhaps, for this animal, any quantity of drug functioned as a discriminative stimulus and its performance became "state dependent" (e.g., Overton, 1967). This finding may also reflect the possibility that the two animals studied used quite different strategies in learning and performing in the tracking situation, and that the drugs studied here selectively affected one of these mechanisms.

VI. Data Acquisition, Analysis and Mathematical Modeling

This section describes work in progress along with the development of a five parameter model to fit the primate data in a compensatory tracking task. A computer iterative scheme of determining the optimal parameters of a given model based on the describing function data is also detailed.

As we had reported earlier (AFOSR Report 75-2751), scheme utilizing the input-output data to define the cross and auto spectra was developed for use with the IBM 370/165 system. The program as developed depends heavily on the random nature of the system signals, and, therefore, much consideration was given to study system identification of known models. The system initially chosen for study is shown in Fig. 1.

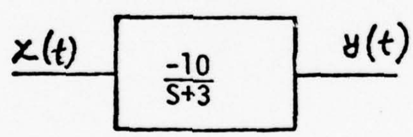


Fig. 1. Linear System (Open Loop) Identification

The above model was simulated digitally using both the standard z-transform and the bilinear z-form techniques. The equation for z-transform is given by:

$$\frac{Y(z)}{X(z)} = \left.\frac{-10}{S+a}\right|_{z = e^{ST}} = \frac{-10T}{1-e^{-aT}z^{-1}} \qquad (1)$$

where $a = 3$

$T = 16$ msec

The bilinear z-transform is given by the following two equations:

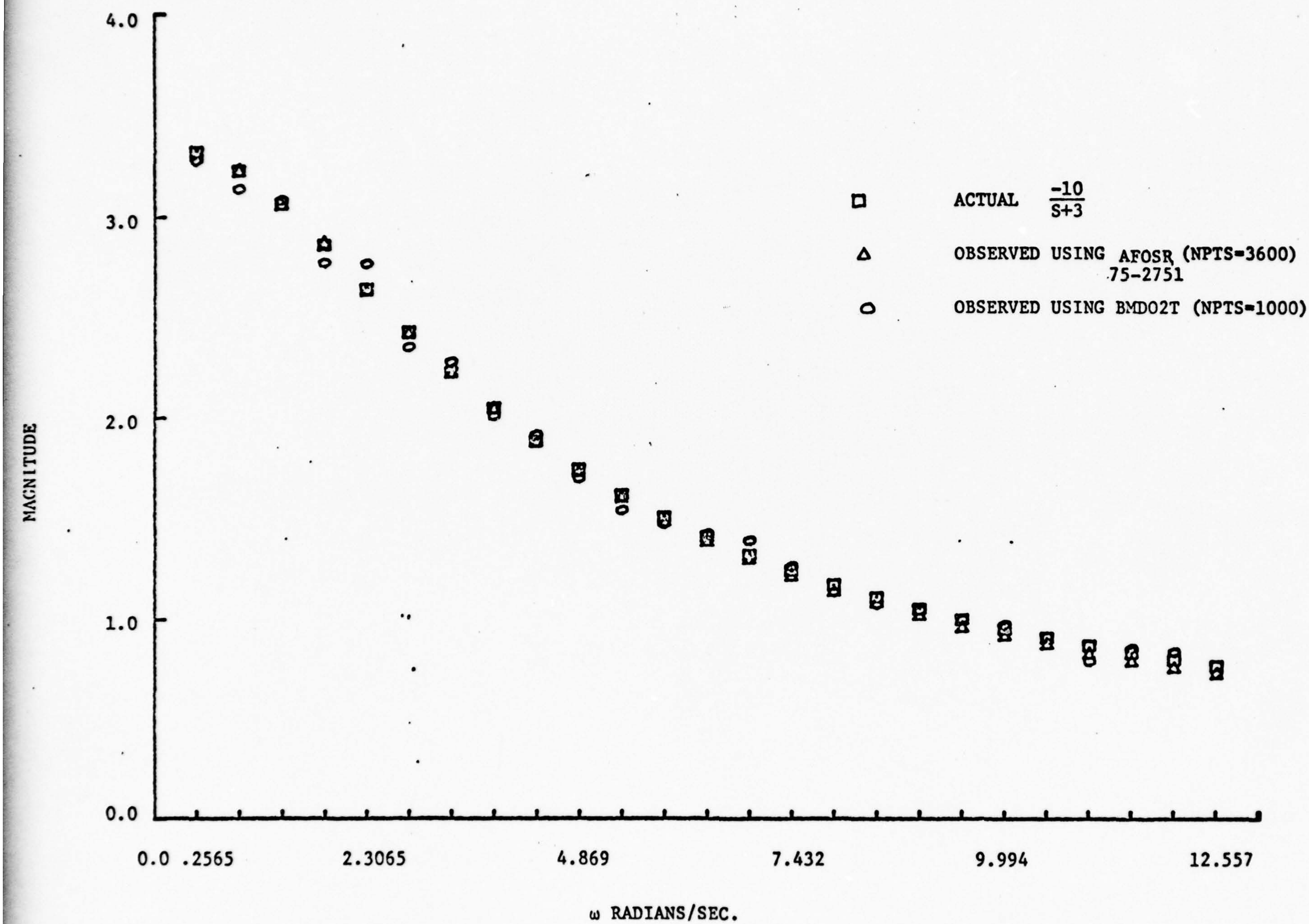


FIG. 2. LINEAR SYSTEM (OPEN LOOP) IDENTIFICATION

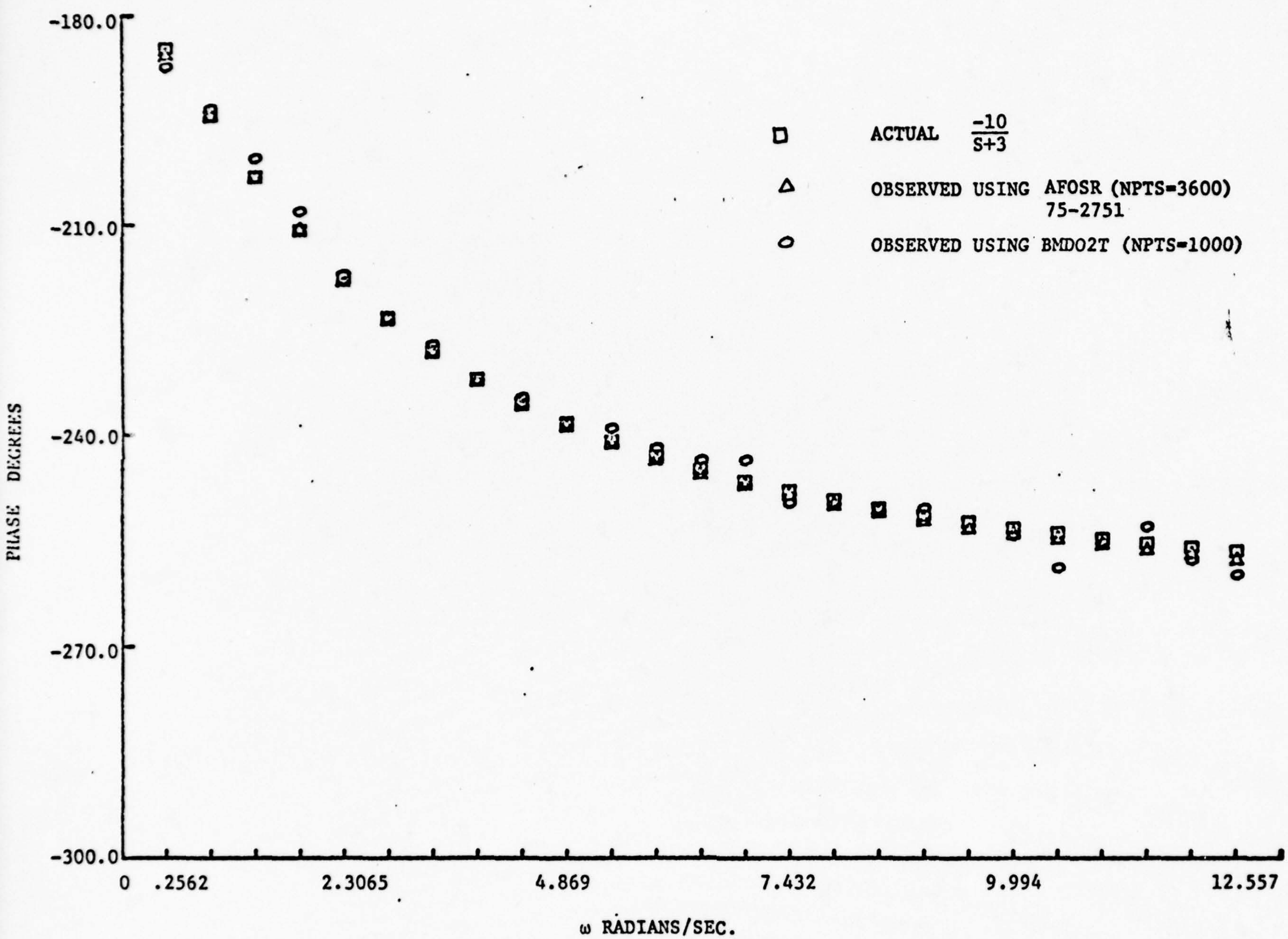


FIG. 2. LINEAR SYSTEM (OPEN LOOP) IDENTIFICATION

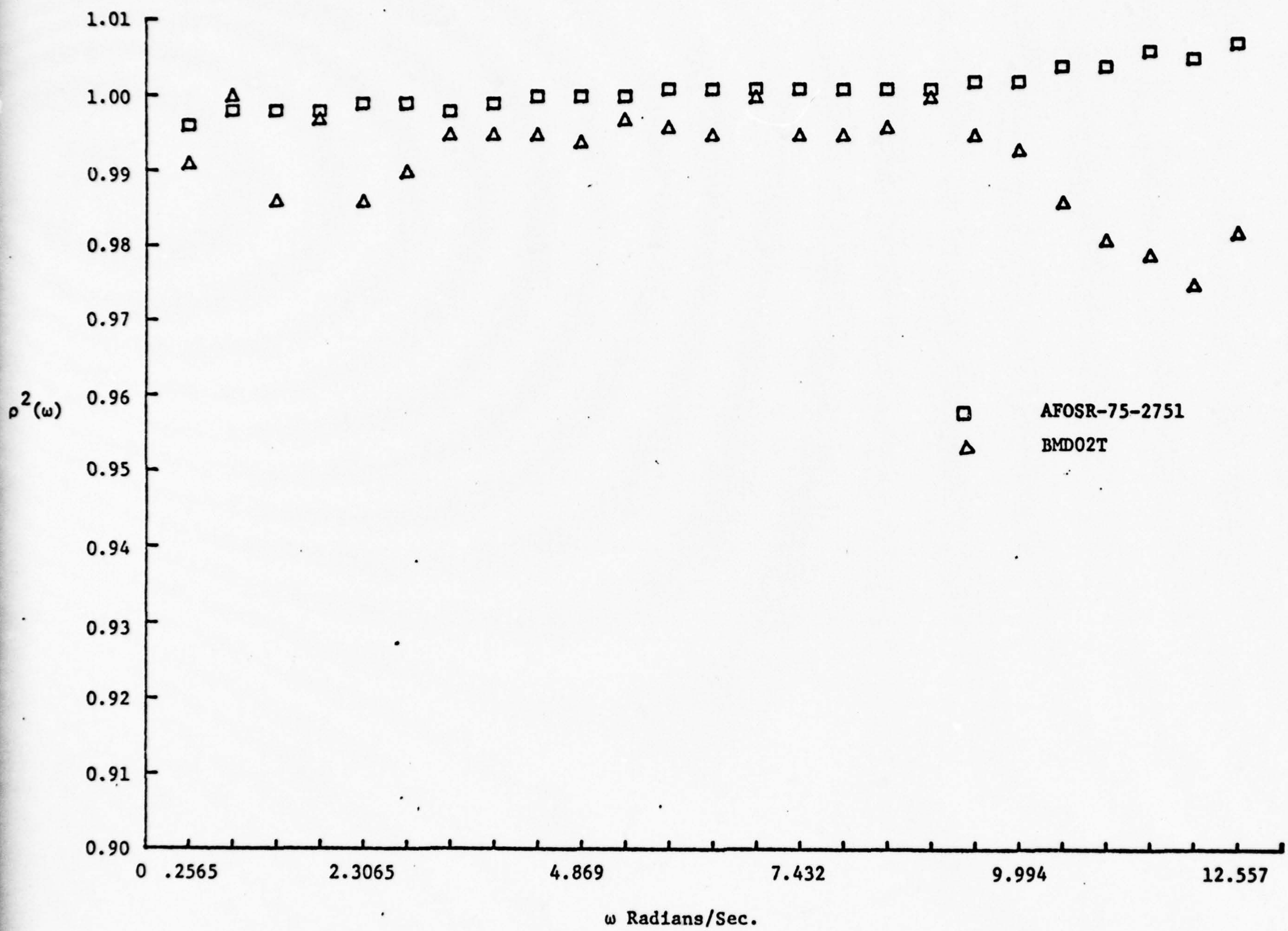


Fig. 3. Linear System (Open Loop) Identification

$$s = \left(\frac{1-z^{-1}}{1+z^{-1}}\right) \frac{2}{T} \tag{2}$$

and

$$\frac{\omega_D T}{2} = \tan \frac{\omega T}{T} \tag{3}$$

Actual and observed magnitude and phase plots are shown in Fig. 2. A comparison of our results were made with a program developed at the University of California (BMD02T). It was observed that our programs fitted the actual results to within an accuracy of 2%. The superiority of our technique is shown in Fig. 3 where the correlation index ρ^2 is computed as a function of frequency. It also should be noted that the cumulative ρ^2 is very nearly (0.99), indicating that the system is linear.

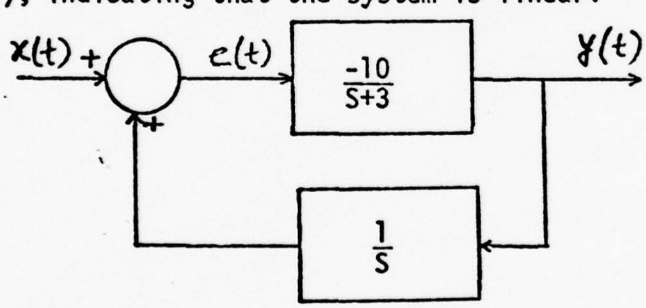


Fig. 4. Linear System (Closed Loop) Identification

In order to test the ability of the program to identify an unknown system in a closed loop configuration, the system shown in Fig. 4 was digitally simulated using equations 4 and 5 to generate Y(KT) and E(KT) respectively.

$$Y(KT) = \{1.232\ (X(K-2) - X(K)) + 7.9241088\ Y(K-1)$$
$$-(4.0379456 - .1232\omega_D)\ Y(K-2)\}/(4.0379456 + .1232\omega_D) \tag{4}$$

$$E(KT) = \{(4.0 + .1232\omega_D)\ X(K) - 8.0\ X(K-1) + (4.0 - .1232\omega_D)$$
$$X(K-2)\ 7.9241088\ E(K-1) - (4.0379456 - .1232\omega_D)\ Y(K-2)\}/$$
$$(4.0379456 + .1232\omega_D) \tag{5}$$

where ω_D is the digital equivalent of the analog cut-off frequency defined by equation 3. The results are shown in Fig. 5, and it is apparent that the program is successful in identifying a closed loop system.

In the following, the developments of the describing function estimates and model identification schemes are described.

1. Describing Function Estimates

The first part of the program combines subroutines FRTRM, SORT6, CROCOR, and PSD, leading to cross-spectral estimates Φ_{io} -- cross-spectra between input and output and Φ_{ie} -- cross-spectra between input and error (AFOSR Report 75-2751) using the conventional definition of describing function (Krendel et al., 1957).

$$Y(j\omega) = \frac{\Phi_{io}(\omega)}{\Phi_{ie}(\omega)} \tag{6}$$

Since both Φ_{io} and Φ_{ie} are complex numbers, the two can be combined to express $Y(j\omega)$ as a complex number.

$$Y(j\omega) = \frac{Re[\Phi_{io}] + jIm[\Phi_{io}]}{Re[\Phi_{ie}] + jIm[\Phi_{ie}]}$$

$$= \frac{(Re[\Phi_{io}] + jIm[\Phi_{io}])}{(Re[\Phi_{ie}] + jIm[\Phi_{ie}])} \cdot \frac{(Re[\Phi_{ie}] - jIm[\Phi_{ie}])}{(Re[\Phi_{ie}] - jIm[\Phi_{ie}])}$$

$$= \frac{[(Re[\Phi_{io}](Re[\Phi_{ie}] + (Im[\Phi_{io}])(Im[\Phi_{ie}])]+j[(Im[\Phi_{io}])(Re[\Phi_{ie}])]}{(Re[\Phi_{ie}])^2 + (Im[\Phi_{ie}])^2}$$

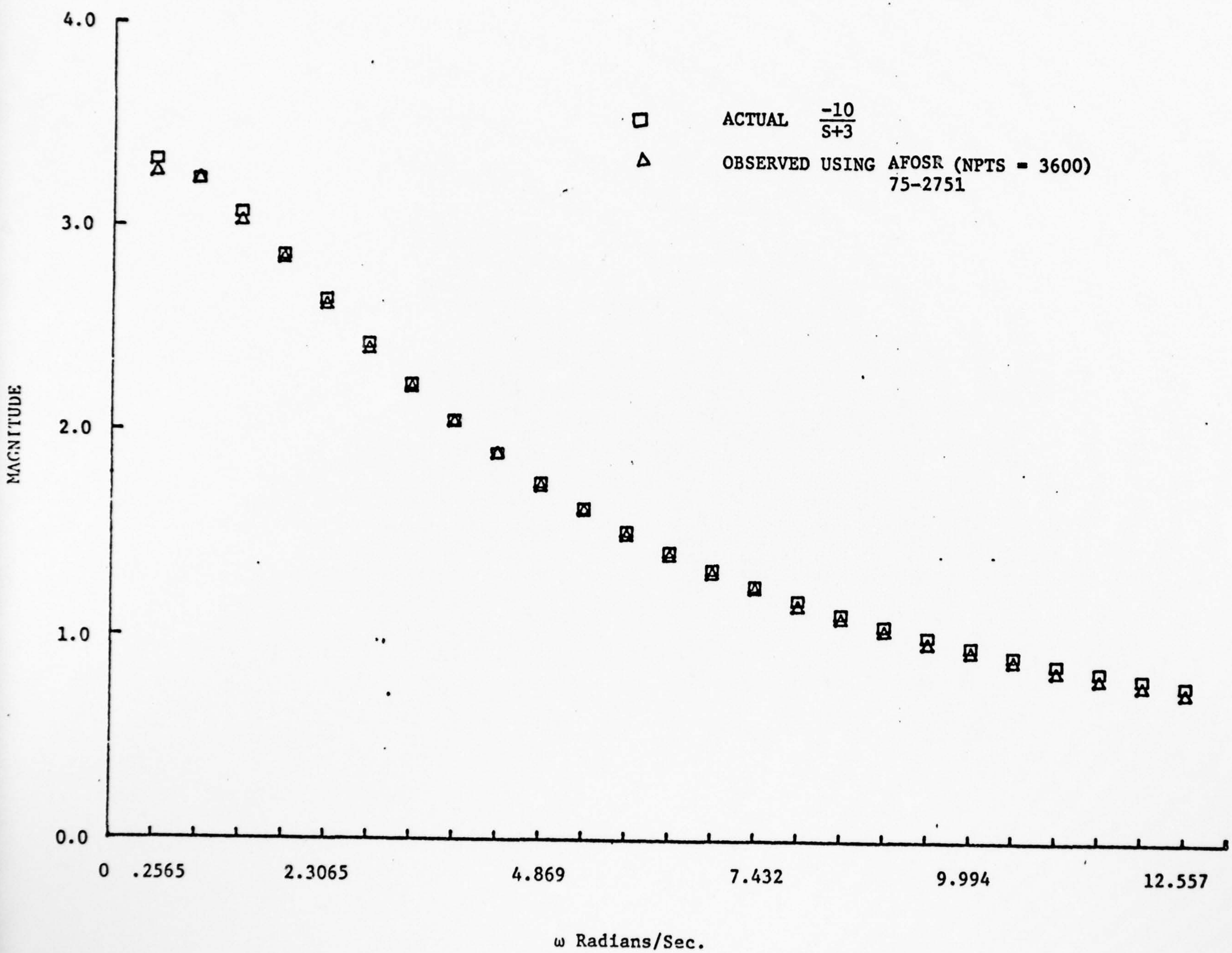


Fig.5 Linear System (Closed Loop) Identification

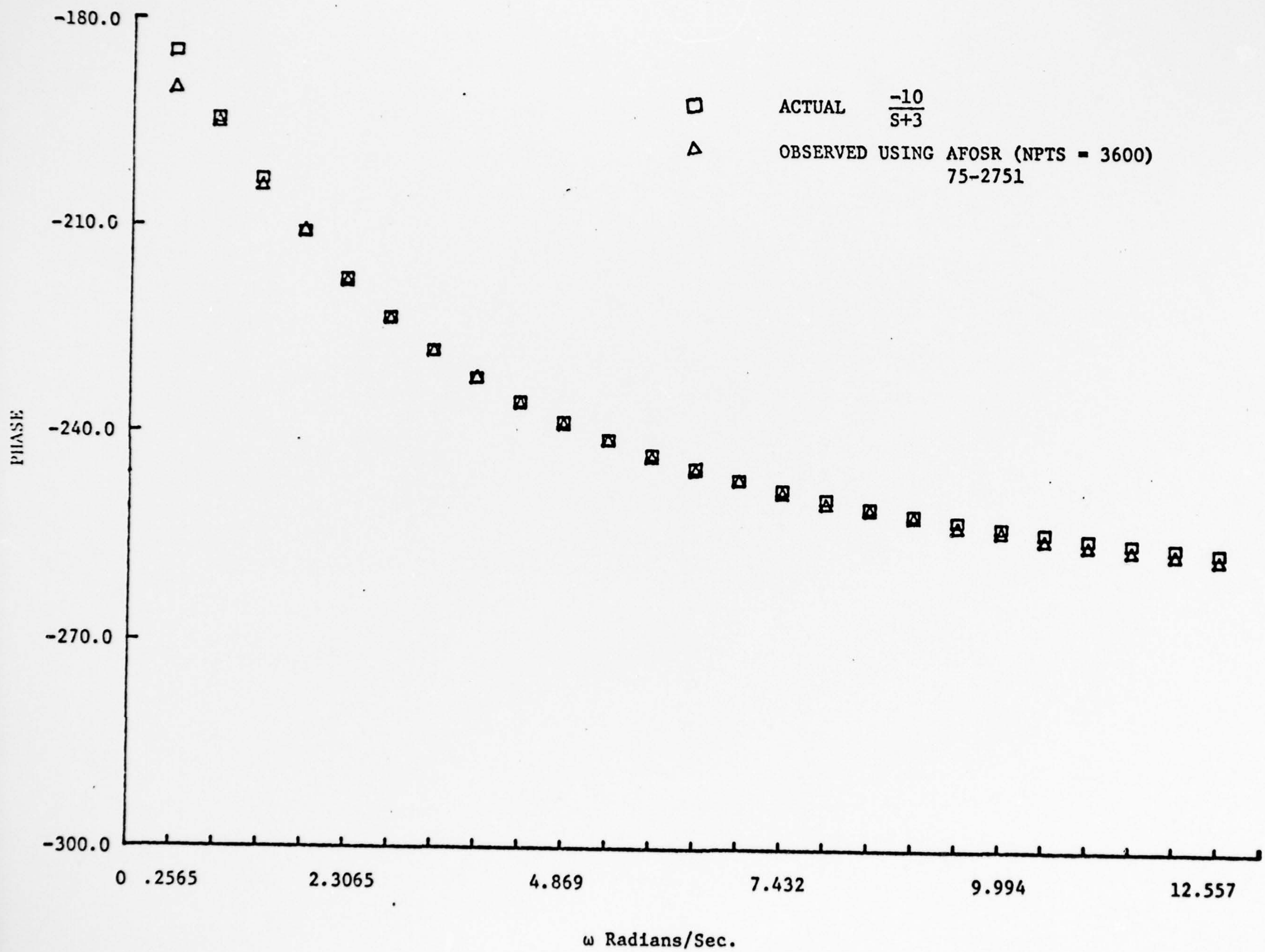


Fig. 5 Linear System (Closed Loop) Identification

$$\frac{-j[(Re[\Phi_{io}])(Im[\Phi_{ie}])]}{(Re[\Phi_{ie}])^2 + (Im[\Phi_{ie}])^2}$$

$$= \frac{[(Re[\Phi_{io}])(Re[\Phi_{ie}]) + (Im[\Phi_{io}])(Im[\Phi_{ie}])]}{(Re[\Phi_{ie}])^2 + (Im[\Phi_{ie}]0^2}$$

$$+ \frac{j[(Im[\Phi_{io}])(Re[\Phi_{ie}]) - (Re[\Phi_{io}])(Im[\Phi_{ie}])]}{(Re[\Phi_{ie}])^2 + (Im[\Phi_{ie}])^2}$$

$$= Y'(\omega + j\, Y''(\omega) \tag{7}$$

2. Model Identification Scheme

The second part of the program assumes a known model which may be expressed as a complex number:

$$G(j\omega) = G'(\omega + j\, G''(\omega) \tag{8}$$

and determines optimal values of various parameters to minimize the sum squared error S defined by

$$S(\overline{A}) = \Sigma\, (G_i' - Y_i')^2 + (G_i'' - Y_i'')^2 \tag{9}$$

where i is a frequency index, G_i' and G_i'' are data computed for the assumed model and Y_i' and Y_i'' are experimentally observed data. G_i' and G_i'' are computed for the chosen model using arbitrarily chosen values of unknown parameters, $\overline{A}$, the dimensions of which depend on the number of parameters in the model.

Differentiation of equation 9 with respect to a given unknown parameter, A_j is given by

$$\frac{\partial S}{\partial A_j} = 2[(G_i' - Y_i') \frac{\partial G_i'}{\partial A_j} + (G_i'' - Y_i'') \frac{\partial G_i''}{\partial A_j}] \qquad (10)$$

Since S is a function of $\overline{A}$, a Taylor series expansion in terms of known values of S and $\overline{A}^o$ may be made ($\overline{A}^o$ is the initially chosen parameter set)

$$S(\overline{A}) = S(\overline{A}^o) + \frac{\partial S}{\partial A_j} \Delta A_j + \text{higher order terms} \qquad (11)$$

Thus, if higher order terms in equation 11 can be neglected an iterative program using equations 7 and 8 may be devised such that $S(\overline{A})$ tends to zero (perfect fit).

The program begins with an arbitrarily chosen parameter vector, $\overline{A}^o$. The upper and lower limits on the unknown parameters are required both to limit the search area and to physically interpret the data. The function value $S(\overline{A}^o)$, G_i', G_i'', and $\frac{\partial S}{\partial A_j}$ are computed using equation 9 and the chosen model. If $S(\overline{A}^o)$ and magnitude of the gradient, $\overline{G}(\overline{A}^o)$, defined by,

$$\overline{G}(\overline{A}^o) = [\frac{\partial S}{\partial A_1}, \frac{\partial S}{\partial A_2}, \ldots \ldots]^T \qquad (12)$$

are less than a specified tolerance the computer search for a local minima is over and a new run may be made with a different starting parameter vector. This is usually not the case whence a move in the negative gradient direction is made to define a new parameter vector

$$\overline{A}^n = \overline{A}^o - \alpha\, \overline{G}(\overline{A}^o) \qquad (13)$$

where α is defined by

$$\alpha = \frac{S(\overline{A}^o)}{<\overline{G}(\overline{A}^o),\ \overline{G}(\overline{A}^o)>} \tag{14}$$

Equations 13 and 14 define the steepest descent formula (McGhee, 1967). At the new vector $\overline{A}^n$ the curve fit error $S(\overline{A}^n)$ is computed and compared with $S(\overline{A}^o)$. If the error has been reduced the new values are assumed and equations 13 and 14 are used recursively. In the event the steepest descent method fails, a second order gradient technique known as Newton Raphson technique (McGhee, 1967) has been incorporated which has good convergence properties in the vicinity of a minima. The new vector $\overline{A}^n$ with this formula is given by

$$\overline{A}^n = \overline{A}^o - [\Phi^T\Phi + \Theta^T\Theta]^{-1}\ \overline{G}(\overline{A}^o) \tag{15}$$

where Φ and Θ are rectangular matrices of partial derivatives of error terms $(G_i' - Y_i')$ and $(G_i'' - Y_i'')$ with respect to the unknown parameters. The process of iterative minimization of sum-squared error continues until no further reduction in S is possible with both the above gradient techniques.

The program is convergent for various starting values chosen for a known model discussed later. It should be noted, however, that since the program is based on the search for a local minima it is entirely possible that a better fit to data may result through choice of a different starting vector. This is known in the literature as starting parameter bias.

The model identification scheme was tested on the following four parameter model given by

$$G(j\omega) = \frac{e^{-\tau S}\ (1 + T_1S)}{(1 + T_2S)(1+T_3S)} \tag{16}$$

The chosen parameter values were τ = 0.2 sec, T_1 = 0.2 sec, T_2 = 0.5 sec, and T_3 = 5.0 sec.

The model identification scheme identified the model parameters as τ = 0.19997, T_1 = 0.19997, T_2 = 0.50005, and T_3 = 4.9980 starting with the arbitrarily chosen values τ = .5, T_1 = .5, T_2 = 2.5, and T_3 = 5.0.

The model identification scheme was also used for a 5 parameter model given by

$$G(j\omega) = \frac{K\, e^{-\tau S}\,(1 + T_1 S)}{(4\ T_2 S)(1 + T_3 S)} \quad . \tag{17}$$

starting with $K = 2.0$

$\tau = 0.2$

$T_1 = 0.2$

$T_2 = 0.5$

$T_3 = 5.0$

A typical set of parameters identified was

$\tau = .20012$

$K = 1.9990$

$T_1 = .2005$

$T_2 = 0.5008$

$T_3 = 4.995$

with S = 0.134970 $\times 10^{-6}$ and Gmax = 0.951132 $\times 10^{-4}$. Several starting parameter vectors were chosen for both 4 parameter and 5 parameter models and results were identical to those discussed above. A typical run with 6 trials took 60 secs, of computer time; i.e., 10 secs for each trial.

The following is the tabulation of final vectors for different initial vectors both for 4-parameter and 5-parameter models.

4-Parameter Model

Run #	# of Iterations	Initial Vector	Final Vector	Cumulative Error
1	119	τ = .5	τ = .2018	$.1964 \cdot 10^{-5}$
		T_1 = .5	T_1 = .2100	
		T_2 = 2.5	T_2 = .5130	
		T_3 = 5.0	T_3 = 4.985	
2	131	τ = .45	τ = .1999	$.1935 \cdot 10^{-5}$
		T_1 = .6	T_1 = .1999	
		T_2 = 4.0	T_2 = .5000	
		T_3 = 5.0	T_3 = 4.9980	
3	83	τ = .3	τ = .1991	$.5527 \cdot 10^{-6}$
		T_1 = .3	T_1 = .1956	
		T_2 = .5	T_2 = .4943	
		T_3 = 5.2	T_3 = 5.008	

5-Parameter Model

Run #	# of Iterations	Initial Vector	Final Vector	Cumulative Error
1	140	τ = .5	τ = .2001	$.1349 \cdot 10^{-6}$
		T_1 = .5	T_1 = .2005	
		T_2 = 2.5	T_2 = .5008	
		T_3 = 5.0	T_3 = 4.995	
		K = 1.0	K = 1.9999	
2	104	τ = .3	τ = .1998	$.1445 \cdot 10^{-6}$
		T_1 = .4	T_1 = .1994	
		T_2 = 2.0	T_2 = .4991	
		T_3 = 6.0	T_3 = 5.0041	
		K = 2.0	K = 2.0001	
3	212	τ = .6	τ = .2001	$.1491 \cdot 10^{-6}$
		T_1 = .6	T_1 = .2005	
		T_2 = 4.0	T_2 = .5009	
		T_3 = 6.0	T_3 = 4.9957	
		K = 2.0	K = 1.9989	

Figure 6 shows the application of our system identification scheme to primate data using a five parameter model. The values of τ = o.1 sec, T_1, 4.5 sec, T_2 = 1.65, T_3 = 8.12 and K = 11.99 were obtained. The data suggest that the primate shows a remarkable similarity in performance to the human in a closed loop situation. However, it should be noted that the present model has been developed at very low frequencies where data for human operators is not available in the literature.

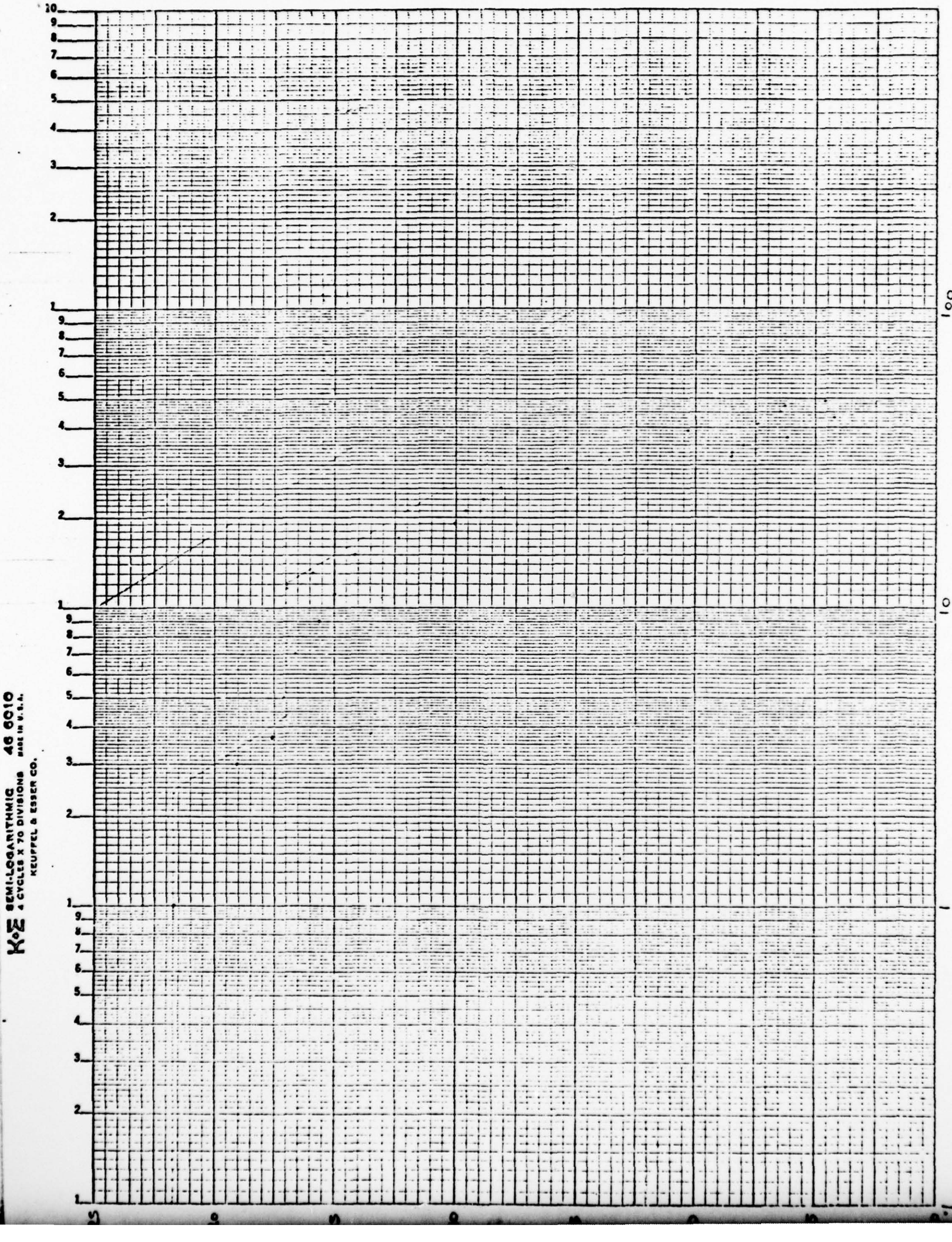
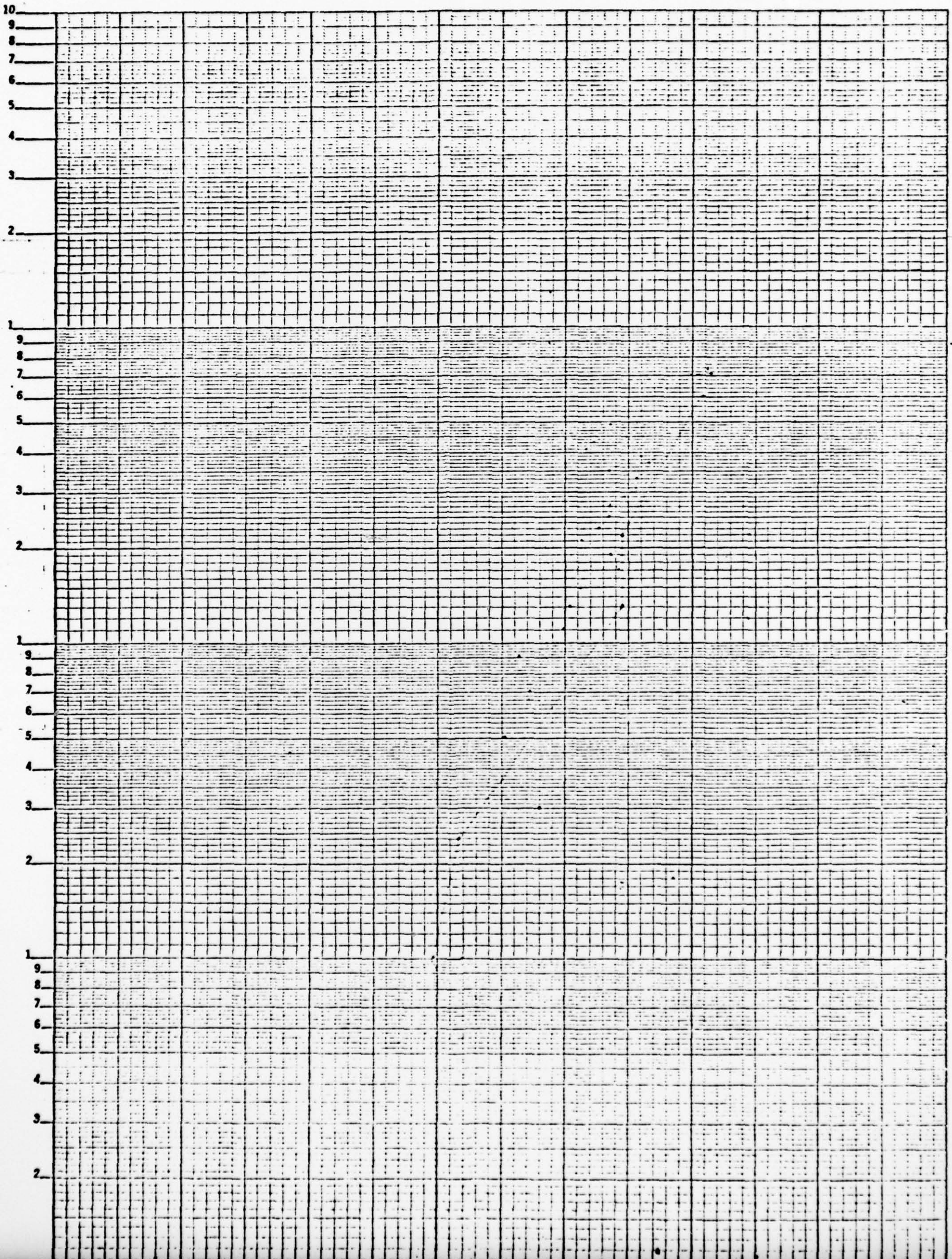


Fig. 6. Magnitude



1
10
100
ω/0.051 rads/sec
K&E SEMI-LOGARITHMIC 46 6010
4 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.

Fig. 6. Phase

It was observed that the five parameter model did not converge to a good visual fit for data recorded for the first run. This is shown in Fig. 7. A check of correlation measure, ρ^2, showed that on the first day it ranged between .5 and .9 where as on a day two weeks later the value ranged between .78 and .98, thereby revealing improvement in backup performance. It also suggests that the animal produces a highly nonlinear response in the early stages and improves towards a linear behavior in subsequent tasks. The tables below show the magnitude and phase data for one particular animal (Hoppy), for five different days chosen randomly. It should be noticed that the deviation is rather large at the lower frequencies. These may be due, in part, to the aliasing introduced by the computational scheme.

OPERATOR NAME=HOPPY

ANALOG SIGNAL BANDWIDTH=0.15HZ

DESCRIBING FUNCTION-MAGNITUDE IN DB

FREQ.	DAY					MEAN	STD. DEV.
	07/12/76	07/13/76	07/20/76	07/26/76	08/02/76		
1	28.02	22.46	14.53	23.27	42.60	26.18	9.29
3	13.18	20.66	17.41	18.41	15.38	17.01	2.56
5	16.70	16.30	12.78	16.37	17.73	15.98	1.68
7	12.00	14.71	12.46	15.39	13.61	13.63	1.29
9	13.21	14.00	10.80	11.04	11.99	12.21	1.23
11	10.83	13.90	13.91	9.05	10.58	11.65	1.94
13	10.90	9.90	12.44	8.80	9.26	10.26	1.30
15	6.09	9.16	11.72	7.69	8.69	8.67	1.85
17	14.83	7.24	10.19	7.24	7.73	9.45	2.91
19	9.83	7.98	10.02	6.88	7.34	8.41	1.29
21	10.89	8.63	8.85	7.93	7.32	8.73	1.21
23	8.52	6.84	6.29	7.44	9.95	7.81	1.30
25	6.79	6.72	9.32	4.14	5.32	6.46	1.73
27	6.99	4.83	4.95	3.18	1.31	4.25	1.90
29	3.40	0.55	3.76	3.69	1.38	2.55	1.33

OPERATOR NAME=HOPPY

ANALOG SIGNAL BANDWIDTH=0.15HZ

DESCRIBING FUNCTION-PHASE IN DEGREES

FREQ.	DAY 07/12/76	07/13/76	07/20/76	07/26/76	08/02/76	MEAN	STD. DEV.
1	-76.68	-125.56	-14.26	-0.76	8.70	-41.7	51.4
3	-60.14	12.38	-32.19	-20.70	-58.38	-31.8	26.8
5	-55.81	-50.77	-22.45	-40.30	-71.81	-48.2	16.4
7	-85.73	-59.38	-36.50	-43.57	-31.03	-51.2	19.7
9	-82.69	-61.35	-55.47	-65.88	-35.32	-60.1	15.4
11	-64.34	-53.76	-41.86	-58.82	-53.80	-54.5	7.4
13	-66.11	-60.97	-48.22	-51.08	-50.97	-55.5	6.9
15	-74.81	-68.19	-38.57	-51.43	-48.76	-56.4	13.3
17	-61.81	-59.79	-51.93	-59.36	-56.64	-57.9	3.4
19	-73.44	-61.56	-54.60	-55.95	-62.91	-61.7	6.7
21	-91.97	-53.05	-64.16	-56.13	-65.99	-66.3	13.7
23	-74.80	-71.29	-79.16	-58.25	-56.90	-68.1	8.9
25	-73.65	-81.17	-73.39	-75.64	-79.39	-76.7	3.1
27	-75.32	-74.14	-92.94	-85.57	-64.71	-78.5	9.8
29	-82.53	-74.54	-95.88	-105.91	-68.37	-85.4	13.9

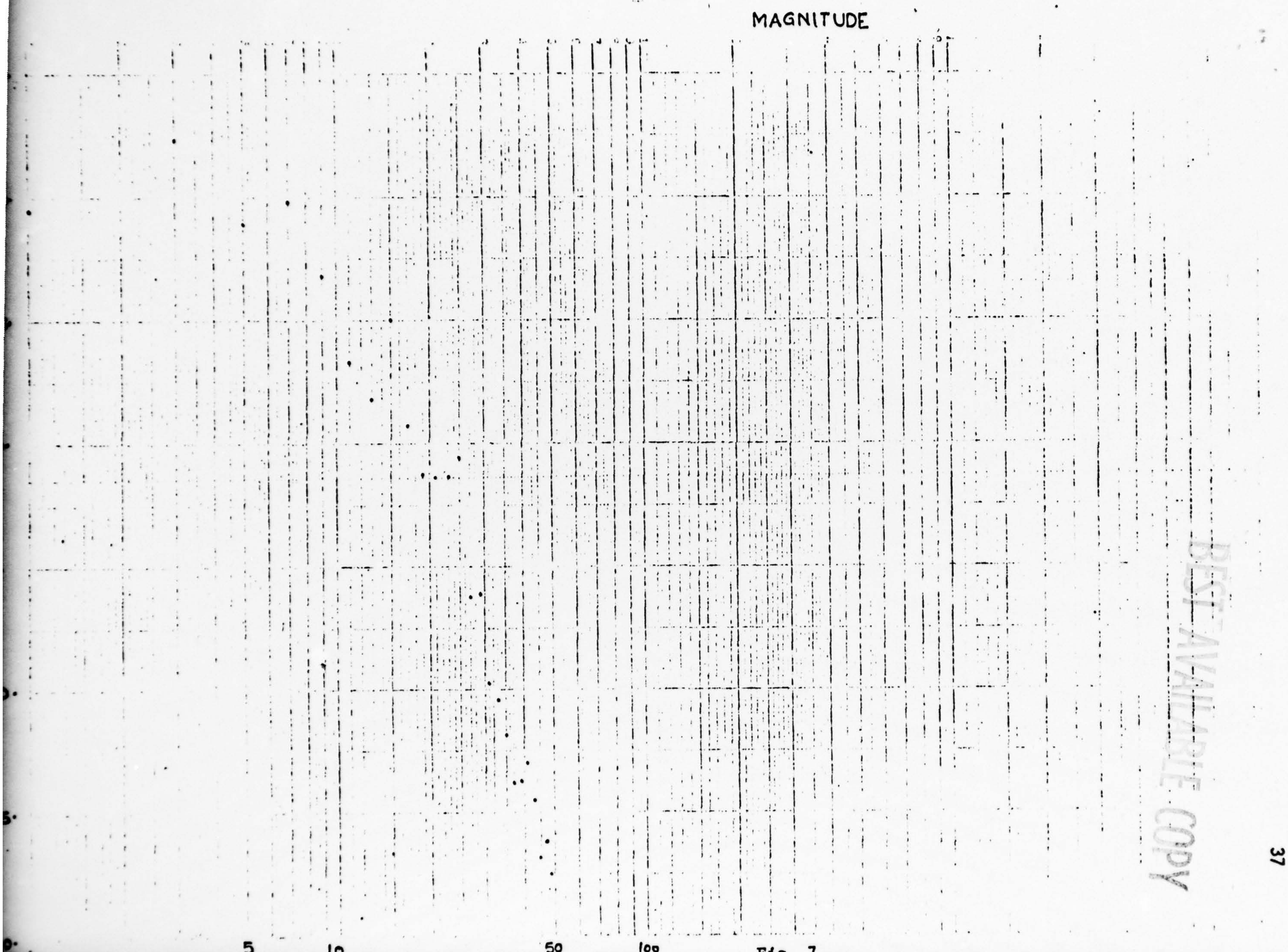


Fig. 7.

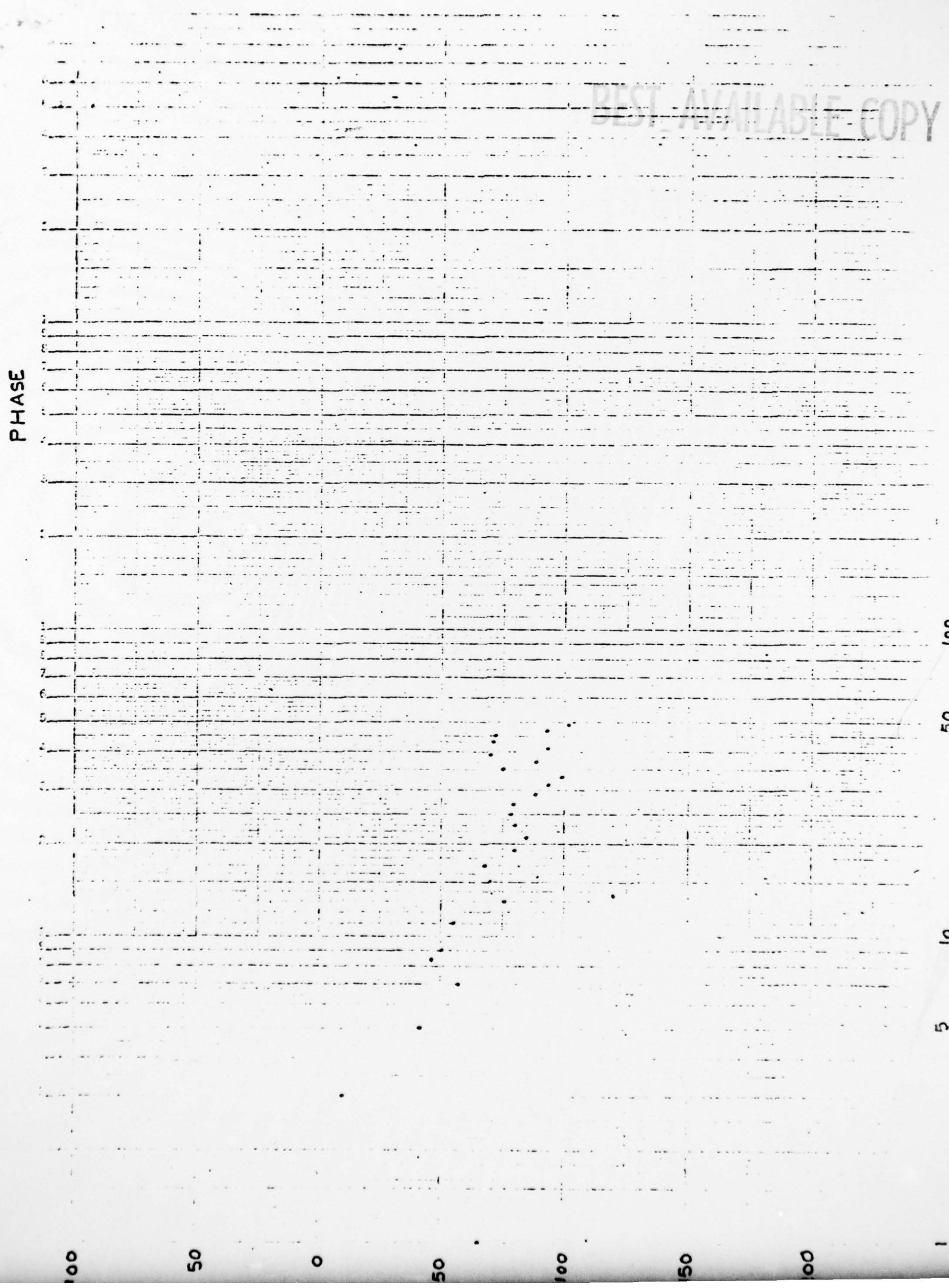


Fig. 7.